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A versatile small-scale structural laboratory for novel experimental earthquake engineering

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Abstract. Experimental testing has been considered as one of the most straightforward approaches to realize the structural behavior for earthquake engineering studies. Recently, novel and advanced experimental techniques, which combine numerical simulation with experimental testing, have been developed and applied to structural testing practically. However, researchers have to take the risk of damaging specimens or facilities during the process of developing and validating new experimental methods. In view of this, a small-scale structural laboratory has been designed and constructed in order to verify the effectiveness of newly developed experimental technique before it is applied to large-scale testing for safety concerns in this paper. Two orthogonal steel reaction walls and one steel T-slotted reaction floor are designed and analyzed. Accordingly, a large variety of experimental setups can be completed by installing servo-hydraulic actuators and fixtures depending on different research purposes. Meanwhile, a state-of-the-art digital controller and multiple real-time computation machines are allocated. The integration of hardware and software interfaces provides the feasibility and flexibility of developing novel experimental methods that used to be difficult to complete in conventional structural laboratories. A simple experimental demonstration is presented which utilizes part of the hardware and software in the small-scale structural laboratory. Finally, experimental layouts of future potential development and application are addressed and discussed, providing the practitioners with valuable reference for experimental earthquake engineering.

Keywords: small-scale structural laboratory; structural testing; advanced experimental technique; earthquake engineering

1. Introduction

Structural testing has been considered essential for assessing seismic responses of structural systems or members in earthquake engineering studies. Servo-hydraulic actuators have been widely used to impose deformation or force on the specimens as they can provide large force capacity and frequency bandwidth. A large number of testing methods have been developed and applied to structural testing for the past decades. Quasi-static testing, which can be either monotonic or cyclic, has been considered the most prevalent method for structural testing in the laboratory. During a quasi-static test, a predefined displacement/force time history profile is generated as the desired response to impose on the specimen with a ramp and hold procedure. Generally, the servo-hydraulic actuators are ramped in 1 second with an extremely slow rate and held for another few seconds to trigger the data acquisition system and collect the data. It is noted that the common update rate of a digital controller of actuators is 1024 Hz, which indicates that each tiny displacement/force control step is within 1/1024 second. For example, a 5-mm displacement target can be separated into five ramp-and-hold steps. In each step, the actuator displacement is ramped in 1 second and held for another 2.5 seconds to have the data acquisition triggered to collect the data as illustrated in Fig. 1. In other words, the actuator is moving with a velocity of 1.0 mm/sec and 1024 control steps for one second. The inertial and damping forces can be neglected because the specimen is deformed slowly; therefore, the displacement-to-force relationship, ductility, dissipated energy, and failure mode of the specimen can be obtained directly and safely. In addition, the dimension of the specimen for quasi-static cyclic testing can be large scale or even full scale because the flow rate requirement of servo-hydraulic actuators is considered moderate (Hou *et al*. 2016, Kim *et al*. 2016).

Pseudo-dynamic testing, also called conventional hybrid simulation, combines numerical simulation and quasi-static testing in order to investigate the seismic response of structures (Nakashima *et al*. 1995). During a typical pseudo-dynamic test, a structure is separated into a numerical model and an experimental specimen that is difficult to simulate and needs to be investigated physically.

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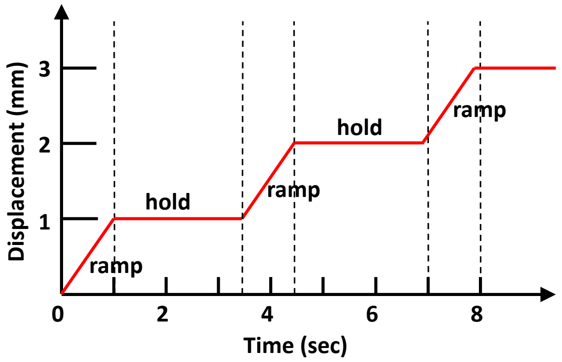


Fig. 1 Illustration of a ramp-and-hold loading history

The interface between the numerical model and experimental specimen is formed by servo-hydraulic actuators and steel fixtures. The displacement response at the interface of the structure subjected to ground motion is obtained by solving the equation of motion through a step-by-step integration scheme. The computed displacement is taken as the target to impose on the experimental specimen quasi-statically by servo-hydraulic actuators. Then, the corresponding force is measured and fed back to the integration algorithm to calculate the displacement response for the next time step. The specimen can be large scale or even full scale for conventional hybrid simulation since the displacement is imposed quasi-statically (Khoo *et al*. 2016). Due to the elapsed time of numerical computation and the movement of quasi-static actuator, there is an expanded time scale for conducting pseudo-dynamic testing which cannot be applied to physical specimens with rate-dependent devices.

Real-time hybrid simulation (RTHS), similar to the architecture of pseudo-dynamic testing, has been proposed for physical specimens with rate-dependent devices. However, the displacement response at the interface between the numerical model and experimental specimen must be imposed on the experimental specimen by servo-hydraulic actuators in real time. Any time lag and delay due to numerical computation, hardware communication, dynamics of actuators, digital controllers, and sensors introduces negative damping into a RTHS which could distort the structural response and even destabilize the entire RTHS (Horiuchi *et al*. 1999). As a result, time lag and delay must be compensated in order to achieve successful RTHS. Various compensation schemes have been proposed to reduce to effects of time lag and delay such as linear acceleration extrapolation (Horiuchi *et al*. 1999), polynomial extrapolation (Darby *et al*. 2002), derivative feedforward compensation (Jung *et al*. 2007), kinematics-based extrapolation (Ahmadizadeh *et al*. 2008), first-order discrete inverse compensation (Chen *et al*. 2009), adaptive second-order discrete phase-lead compensation (Chen and Tsai 2013), adaptive time series compensation (Chae *et al*. 2013), and optimal discrete-time compensation (Hayati and Song 2017). Recently, seismic shake tables have been adopted to conduct RTHS which is called hybrid shake table testing (Schellenberg *et al*. 2017). Hybrid shake table has been applied to investigate the seismic response of a structure with a tune liquid damper (Wang *et al*. 2016) and an inter-story-isolated building (Zhang *et al*. 2017). These aforementioned advanced experimental approaches need development and validation prior to real application; however, potential risks have to be taken such as system instability and computational divergence.

In order to mitigate the risk during the development and validation process of novel experimental methods, a small-scale structural laboratory (SSL) has been planned, designed, and constructed in National Center for Research on Earthquake Engineering (NCREE) of Taiwan in 2017. It consists of necessary software and hardware for verifying the effectiveness and robustness of newly developed experimental techniques before they can be applied to large-scale testing systems properly. The integration of hardware and software interfaces is considered thoroughly for future development of novel experimental methods. Meanwhile, the feasibility of the developed experimental approach which will be applied in large-scale testing can be confirmed in an economical and efficient manner in the SSL as the specimen dimension is small. In this paper, the design and analysis of the reaction wall and floor are described in detail first. Then, the hardware and software that are essential to future development of novel and advanced experimental techniques are introduced. Afterwards, a general-purpose multi-degree-of-freedom nonlinear specimen is presented. Finally, a real-time hybrid simulation that utilizes the facilities in the SSL is demonstrated. Future potential application such as an experimental framework which combines a seismic shake table and a servo-hydraulic actuator is also addressed at the end of this paper.

2. Design and analysis of reaction walls and floor

The overall design and analysis of the reaction walls and floor is introduced in this section including the finite element modal analysis, and static loading analysis.

2.1 Design requirements

The SSL is a 7890 mm x 7240 mm rectangular indoor area which used to be a material laboratory with a universal testing machine; therefore, hard lines for hydraulic fluid have been allocated underneath properly from the hydraulic power units to the SSL. The design criteria need to consider the available space and the loading capacity of the slabs in the SSL. For the reaction walls, two reaction walls are installed perpendicular to each other such that potential experiments that require two-degree-of-freedom control in the orthogonal horizontal directions are able to be conducted in the future. Each reaction walls and the reaction floor have to be a unitary structure connected by bolting and welding such that the rigidity and homogeneity can be confirmed. CNS SS400 or other with equivalent grade of steel is required for the reaction walls and floor. The clear height of the reaction wall is limited by the loading capacity of the slabs. Generally, the reaction wall should be as high as it can be in order to maximize the

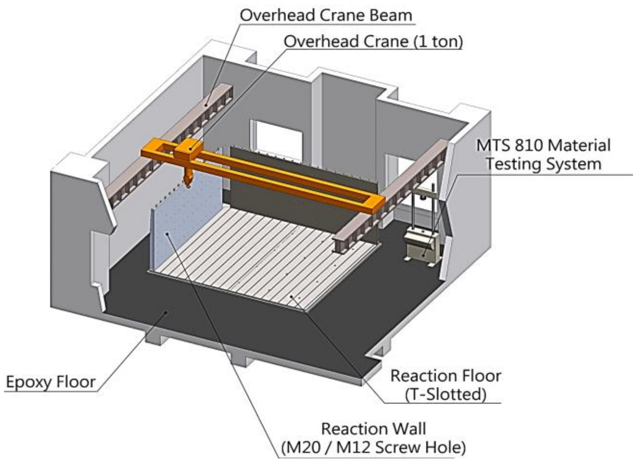


Fig. 2 Schematic of the small-scale structural laboratory

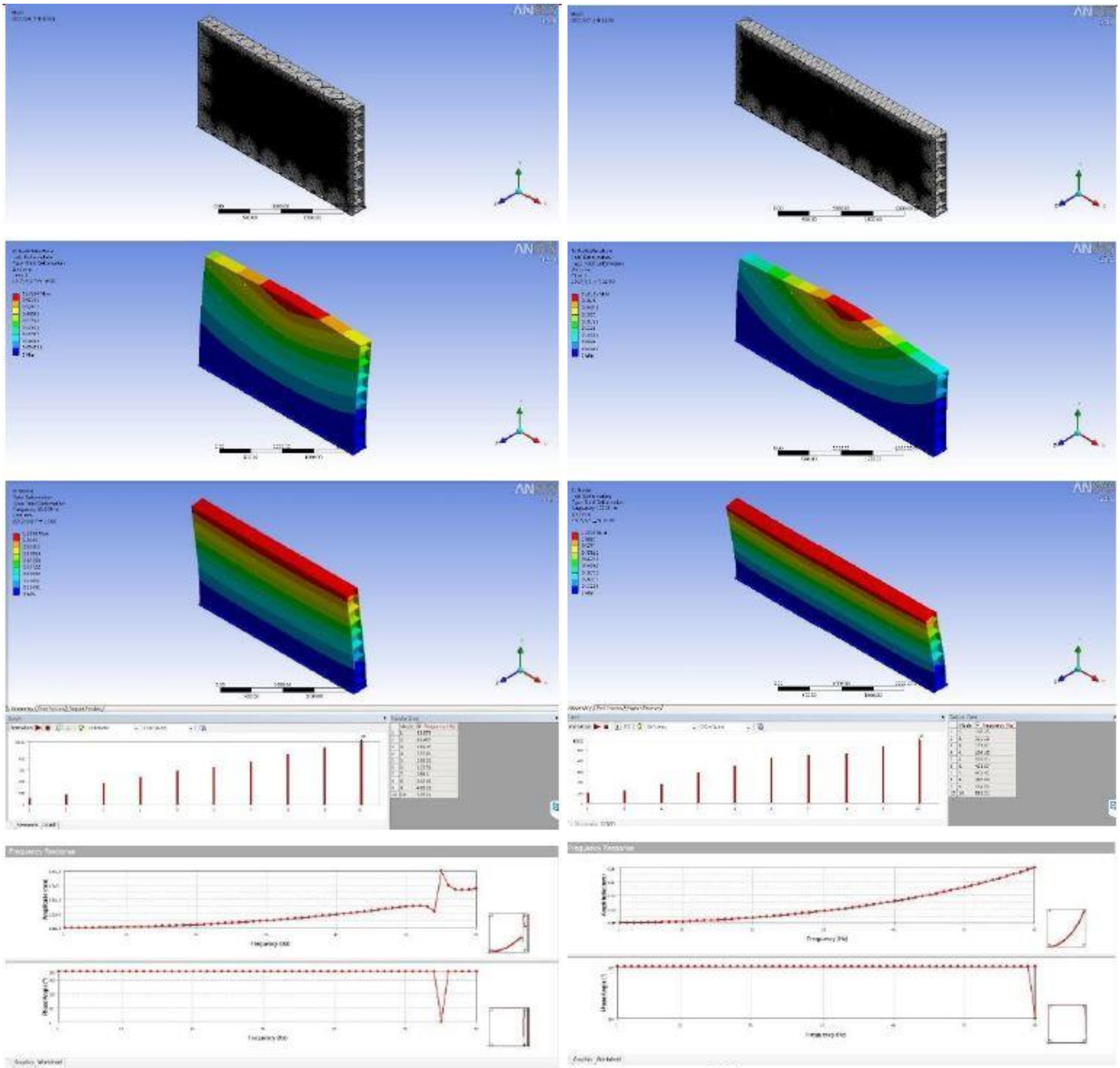
operating area of testing. However, making high reaction wall and sustaining its structural strength, modal frequency and frequency response requires more material and increases the total weight of the reaction structure. The total weight that the laboratory floor can hold is limited and thus limit the maximum height of the reaction wall. Therefore, the height of the reaction wall has an upper bound because of the loading capacity of the laboratory floor. However, the reaction wall should be also high enough to provide sufficient space for testing. Moreover, the two reaction walls should be different in height in order to reduce the self-weight of one wall and adapt various testing requirements. Accordingly, the clear height of the one reaction wall should be larger or equal to 2.0 m while the other should be larger or equal to 1.5 m. Besides, connectors have to be designed and embedded in the short wall for future height extension if necessary. The reaction floor is made of steel and T-slotted in one direction which is used for mounting specimens, actuators, fixtures, and sensors for measurement. Screwed holes interlaced for M20 and M12 high tension bolts are distributed on the surface of the reaction walls and floor for connecting the specimen, actuators and fixtures. Meanwhile, the reaction walls and floor must be rust-proofed by painting or electroplating. For alignment accuracy, the flatness error of the reaction walls and floor must be smaller than ±0.1 mm which has to be confirmed by a laser level. Besides, the interface between the reaction floor and the slab of the laboratory must be grouted with non-shrinkage mortar. The average loading of the entire set of reaction walls and floor, including the weight of welding, bolts, and the other embedded connectors, cannot exceed 5 kN/m^2 for safety concerns. The schematic of the SSL is depicted in Fig. 2. The elevation of the two reaction walls is 2.0 m and 1.5 m, respectively with the widths of 3.5 m and 4.5 m. The reaction floor is a 4.85 m x 4.35 m rectangular area and a thickness of 50 mm. The first natural frequency of the two reaction walls and the reaction floor must be greater than 25 Hz which has to be verified by conducting finite element analysis. Meanwhile, the maximum deformation of each reaction wall cannot exceed 5 ‰ of its clear height when applying 60 kN static loading at the top of the reaction wall. Furthermore, the maximum deformation of the reaction floor cannot exceed 0.5 mm when applying 60 kN static loading at any position on the reaction floor. The abovementioned deformation requirements have to be verified by conducting finite element analysis as well.

2.2 Finite element analysis

Finite element modal analysis and static loading analysis were conducted using the commercial software ANSYS with tetrahedral elements. The minimum element size was less than one-tenth of the minimum size of the real component. It is noted that the reaction floor was too large to be fabricated in one piece. Hence, it was separated into two pieces, namely floor-1 and floor-2, and fabricated in the laboratory on-site. Accordingly, there were 9,557,717, 10,619,686, 7,452,411 and 7,079,790 elements for the 2.0-m reaction wall, the 1.5-m reaction wall, the reaction floor-1, and floor-2, respectively. The boundary conditions were formed according to the actual fabrication and stress conditions. Therefore, fixed boundary condition were assigned at 28, 36, 45, and 45 circular areas for the 2.0-m reaction wall, the 1.5-m reaction wall, the reaction floor-1, and floor-2, respectively. These fixed circular areas were used for connecting the reaction floor to the grouted slab, and for connecting the reaction walls to the reaction floor in actual installation. For material properties, the density, Yang's modulus, Poisson's ratio, yield stress, and fracture stress of the steel were 7850 kg/m^3, 235 GPa, 0.27, 250 MPa, and 460 MPa, respectively. The analysis results show that the maximum deformation and the maximum strain of the reaction floor-1 are 0.26 mm and 0.4%, respectively. Meanwhile, the maximum deformation and the maximum strain of the reaction floor-2 are 0.39 mm and 0.08%, respectively. In addition, the maximum deformation, the maximum strain, and the first natural frequency of the 2.0-m reaction wall are 0.67 mm, 0.2‰, and 55.08 Hz, respectively. The maximum deformation, the maximum strain, and the first natural frequency of the 1.5-m reaction wall are 0.302 mm, 0.03‰, and 100.35 Hz, respectively. It is evident that these analysis results satisfy the design requirements. The analytical setting and results are graphically shown in Fig. 3 including the graphics of mesh, static loading deformation, modal analysis and vibration frequency, and frequency response of the 2-m and 1.5-m reaction walls, respectively.

2.3 Practical realization

Detailed design was conducted by using a computer aided design (CAD) software Solidworks in order to realize the robust reaction walls and floor in the SSL within the total weight limitation. The total weight of the reaction walls and floor divided by the area of structure on the construction floor is taken as the loading pressure which cannot exceed 5 kN/m^2. In the design stage, honeycomb concept was applied to designing the actual reaction structure model in order to keep the strength-to-weight ratio high enough for both the reaction walls and the reaction floor. By this concept, the necessary strength of the reaction



(a) 2.0-m reaction wall (b) 1.5-m reaction wall

Fig. 3 Excerpted finite element analysis results (from top to bottom: mesh, static loading analysis, modal analysis, and frequency resonance)

structure can still be achieved with thinner steel plate and less material. The optimization process has been carried out to verify the optimized design solution for maximum structural strength and most robust frequency response within the total weight limitation of the floor. The detailed CAD model was helpful to reducing the gross weight by optimizing the size of each steel plate and the whole structure. This model was also used as the finite element analysis model to confirm if the natural frequency and the deformation under loading were still satisfied with the design specification.

Steel-web-weldment structures were made in order to practically achieve the honeycomb structure for the reaction walls and floor as shown in Fig. 4. Each web was specially designed to connect with other webs, surface and back plates, and cut by laser cutting machine to ensure the manufacturing precision. The webs were first welded to the surface plate of the reaction wall structure and then welded to each other to form a one-piece structural entity. Annealing and normalizing process was performed to reduce the deformation, and release the internal stress after welding. The screw holes and T-slots for future specimen and actuator installation as well as the structural connection between the reaction walls and the reaction floor were machined by a CNC milling/drilling machine for the finishing of the working surface. Adequate machining

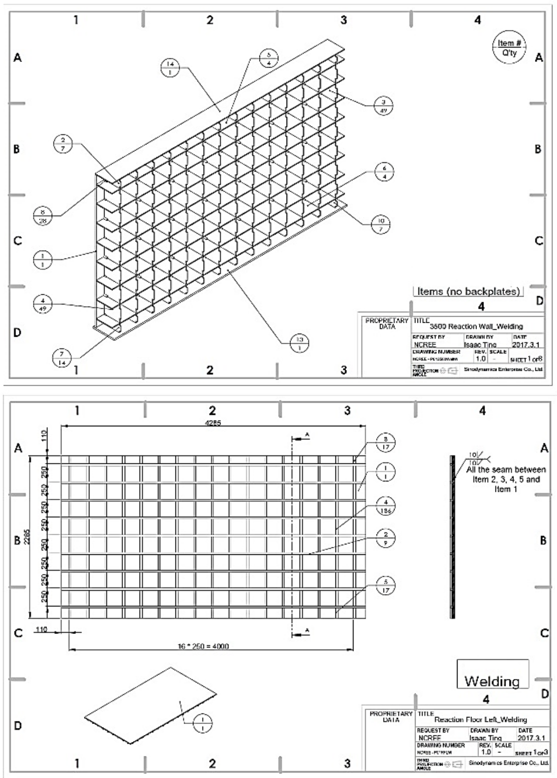


Fig. 4 Honeycomb design of the reaction walls and reaction floor

tolerances were set to ensure that the geometrical and dimensional errors of the final reaction structure were within the criteria of the design specification fairly well. The total weight of the finished reaction structure is 99.82 kN and the corresponding loading stress from the weight is 4.75 kN/m^2.

To firmly fix the reaction floor to the construction structure of the SSL, chemical anchors were applied and installed after the reaction floor was positioned. Laser line level was applied to verify the installation accuracy of the reaction structure. Non-shrinking grout was poured into the gap to create steady and well-distributed contact between the reaction floor and the construction slab. All bolts of the reaction structure were locked and torqued to recommended torsion, creating the preload for each connection of the whole structure. Accordingly, the reaction structure is able to withstand the fatigue load and vibration transmitted from the specimens in future testing.

3. General-purpose hardware and software framework

For the past decades, advanced experimental methods for earthquake engineering studies have been developed and validated by using modern hardware and software. For example, the hybrid simulation framework in the Pacific Earthquake Engineering Research Center (PEER) has mainly adopted OpenFresco as a middleware which links computational software to control software (Schellenberg *et al.* 2009). Even though OpenFresco can be used to interface with numerous modern control and data acquisition systems, PEER mostly completed hybrid simulation by employing OpenFresco with xPC Target and MTS 493 real-time controller communicated by Shared Common Random Access Memory Network (SCRAMNet). On the other hand, UI-SimCor is a software platform designed for distributed hybrid simulation (Kwon *et al.* 2005). It separates an entire structure into a main structure and several substructures interfaced by nodes which can be obtained by applying static condensation. The mass and damping properties of the entire structure as well as the external force are defined in the main structure. Substructures can be divided into numerical substructures and physical substructures that are actually tested in the laboratory. Dynamic analysis of the main structure can be conducted by using a step-by-step integration process. The restoring force from each substructure system is required in the analysis process which can be obtained by the numerical model or actual experimental measurement. The displacement and force data between the main structure and the substructure are transmitted by the internet. The two frameworks mentioned above are focused on slow or fast hybrid simulation. However, recent developed advanced techniques are mostly related to RTHS and distributed real-time hybrid simulation (DRTHS).

3.1 Hardware and software framework

This section provides the specifications of the hardware and software that are crucial to future potential application and experimental configuration in the SSL including the hydraulic and control systems, real-time computation platform, replaceable nonlinear experimental specimen, and etc.

3.1.1 Hydraulic and control systems

The SSL is equipped with six dynamic servo-hydraulic actuators with maximum stroke and force capacity of ±127 mm and ±15 kN, respectively. An MTS FlexTest® Controller FT-100 digital controller is used to control each actuator with a two-stage servo valve that provides a maximum flow rate of 57 liters per minute. In addition to the analog and digital I/O channels, SCRAMNet GT200 is available for high-speed, ultra-low-latency data transfer among most of the real-time computing platforms in the SSL. For hydraulic power, an MTS SilentFlo™ 515 Hydraulic Power Unit (HPU) can supply a maximum sustainable flow rate of 227 liters per minute under 20.68 MPa hydraulic pressure. It is noted that current HPU layout is not able to provide each actuator with maximum flow rate when six actuators are used simultaneously. It is conceivable to extend the hydraulic flow rate if it is necessary in the future. Meanwhile, two hydraulic service manifolds (HSM) with a nominal flow rate of 189 liters per minute are available in the SSL. Each HSM serves a maximum of three actuators simultaneously, providing independent pressure regulation of hydraulic fluid to a maximum of two test stations. Fig. 5 illustrates the potential configuration of the hydraulic and control systems with a total number of six actuators in real practice. Each

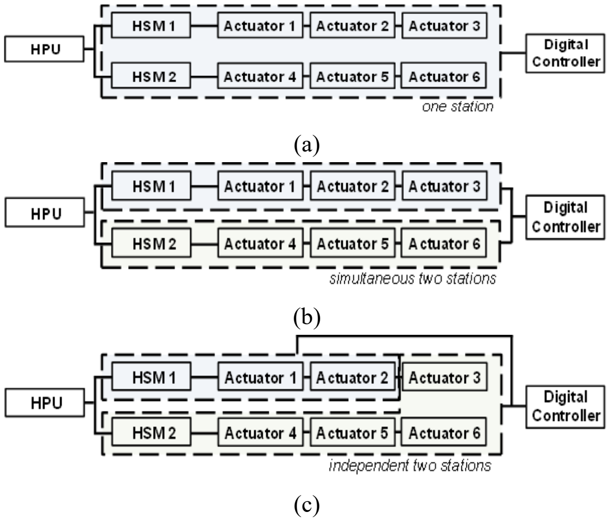


Fig. 5 Experimental configuration of the hydraulic and control systems (a) one station (b) simultaneous two stations (c) independent two stations

block with dashed lines represents one experimental station. For the first option, users can use all the six actuators for one single experiment. For the second option, users can complete two experiments simultaneously by using three actuators for each experiment. Noted that one HSM can support three stations at most by using hand valves; however, any two of the stations cannot be running simultaneously because they share the same HSM. Consequently, for the third option, the two experiments cannot be conducted simultaneously as long as there are more than three actuators used for one of the experiments.

3.1.2 Real-time computing platform

Three different real-time computing platforms are accessible in the laboratory. The first platform is a dSPACE™ MicroLabBox which is able to conduct real-time computation with low I/O latencies. For the I/O channel numbers, 32 analog input, 16 analog output, and 48 bidirectional digital I/O channels are available. Xilinx Kintex®-7 Field Programmable Gate Array (FPGA) is available in MicroLabBox, providing a capability of fast computation of numerical analysis. Meanwhile, MicroLabBox is supported by Real-Time Interface (RTI) for MATLAB®/Simulink® for rapid controller implementation with exceptional I/O integration. GNU C compiler can be used to compile the real-time Simulink-based control loop and generate executable object code for the MicroLabBox processors. In addition, an experiment software ControlDesk is used to access the real-time application during the validation of newly developed experimental methods with a user-friendly interface. The second platform is a National Instruments™ (NI) PXI system which is composed of a chassis, a controller, and modules that can be specialized for each user. The NI PXI system in the SSL provides high-performance measurements, real-time computation, and synchronization for experimental validation. For the I/O channel numbers, 88 analog input, 10 analog output, and 24 bidirectional digital I/O channels are available. Similarly, Xilinx Kintex®-7 FPGA is accessible, providing flexible and customizable I/O for LabVIEW™ FPGA. In addition to LabVIEW™, which is used for control-loop implementation and signal measurements for newly developed novel experimental methods, VeriStand™ is also installed in the system. It provides an environment for configuring real-time test applications and extending with other programming languages for modeling and computing without programming knowledge. The last platform is a xPC Target from the Mathworks® which provides a prototyping environment for connecting Simulink® models to experimental specimen in real time on a personal computer. Therefore, the performance-to-cost ratio of the xPC Target™ is higher than the other two real-time computing platforms in the SSL. Meanwhile, xPC Target™ is also supported by FPGA. However, the I/O expandability is limited to the number of slots on the motherboard. It is noted that the xPC Target™ and the PXI are also equipped with SCRAMNet GT200, which can simultaneously handle network data streams between the MTS FlexTest® Controller FT-100 digital controller and the computing machine.

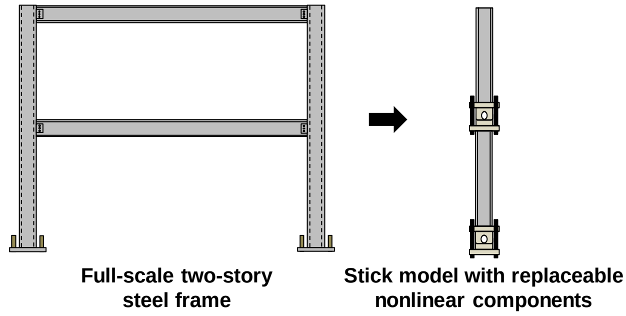


Fig. 6 Illustration of the simplified two-story stick model

3.1.3 Steel specimen with replaceable nonlinear components

Lumped mass stick models have been commonly used in investigation of seismic behavior of structures because of the simplicity and computation efficiency (Chopra 1995). In order to provide the researchers with a replaceable nonlinear specimen for validating newly developed multi-degree-of-freedom real-time control methods in the future, a two-story stick-model steel structure has been designed and fabricated which can be simulating a full-scale two-story steel frame in large structural testing as illustrated in Fig. 6. The story heights of the first and second stories are 752 and 873 mm, respectively. As shown in Fig. 7, each story is composed of three main components: (1) one transfer column serving as the stick, (2) one pin-support, and (3) two pairs of round-bar metal coupons (four coupons in total). The top half of each story is constituted by a transfer column. The SS400B steel H-shape H100×100×6×8 beams are employed to make the transfer columns. The four numbers identified above for Taiwan H-shape section respectively represent the depth, flange width, web and flange thicknesses (in mm). A pin-support made of A572 Gr. 50 steel is placed underneath each transfer column, constituting the bottom half of each floor. The adjacent pin-

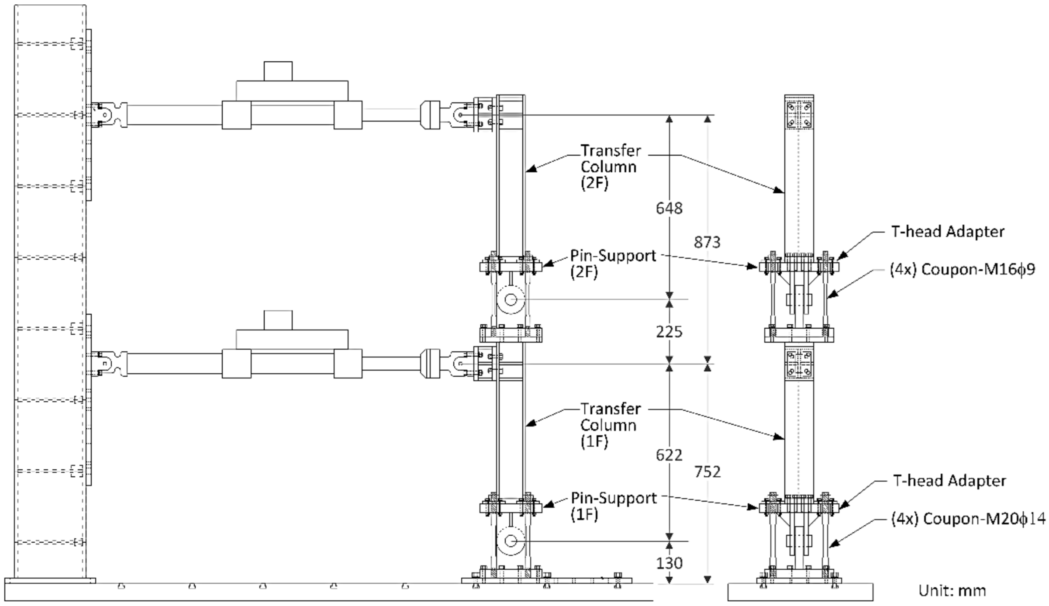


Fig. 7 Experimental setup of the steel specimen with replaceable nonlinear components

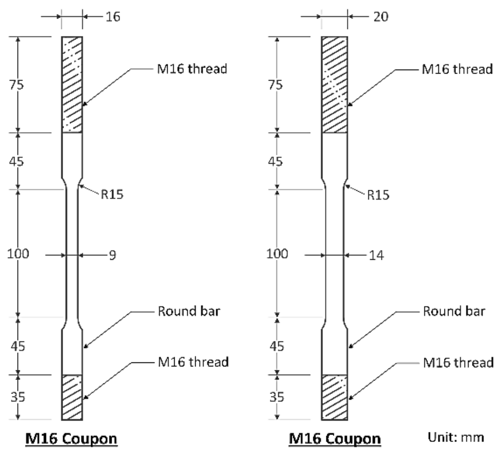


Fig. 8 Dimension of the replaceable nonlinear components

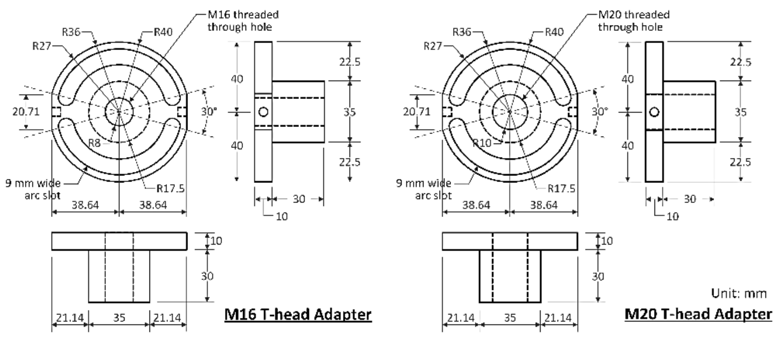


Fig. 9 Details of the T-head adapter

supports and transfer columns are connected through bolts. Two pairs of round-bar metal coupons are installed between the top and bottom plates of the pin-support such that a rotation of the pin-support will cause the elongation of one pair of the coupons and the shortening of the other pair. The axial actions of the metal coupons contribute the rotational stiffness and strength to the pin-support. As a result, the combination of the pin-support and the coupons behaves like a rotational spring.

The specimen can be mounted to the strong floor at the bottom of the first-story pin-support. Two horizontal actuators can be installed between the reaction wall and the specimens to apply the horizontal force to the top end of the transfer column in each story. Once a horizontal displacement is applied at the column top end, a rotation of the pin-support is triggered. In addition, the transfer columns and the pin-support are designed much stiffer and stronger than the metal coupons. Therefore, the deformation of the structure would concentrate at the axial elongation and shortening of the coupons when the specimen is subjected to the lateral sway. Furthermore, the inelastic axial behavior of the coupons can provide the nonlinearity to the structure. Thus, the metal coupons were designed as replaceable structural fuse for this system and the transfer columns and pin-support were designed to remain essentially elastic. By changing the dimensions and material of the metal coupons, the stiffness, strength and nonlinear behaviors of the rotational spring at each pin-support can be tuned. Fig. 8 shows the details of the replaceable coupons. Two sets of round-bar coupons were made of A36 steel. Each coupon has two shoulders and a reduced section in between. The shoulders are larger and threaded at the end of each shoulder, whereas the reduced section has a smaller cross-section so that the plastic deformation and fracture would occur in this area. One set of coupons have a reduced section with 9-mm diameter and M16 threads in the ends while the other set use a 14-mm diameter reduced section and M20 threads. The bottom end of each coupon is threaded into the bottom plate of the pin-support. On the other hand, the top end of each coupon is connected to the top plate of the pin-support using through a T-head adaptor manufactured from the S45C steel. As shown in Fig. 9, in the center of the T-head adaptor, there is a threaded through hole for connecting the adaptor and the coupon top end. In addition, there are two arc slots in the adaptor for accommodating the bolts connecting the T-head adaptor and the pin-support top plate. Using this T-head adapter allows a simple removal of the tested coupon even though the coupon buckles severely in compression.

3.1.4 Others

In addition to the real-time computing platforms mentioned previously, a high-performance computing system powered with a graphical processing unit (GPU) is equipped for numerical structural analysis in the SSL. It is known that significant elapsed time is required for predicting and correcting the dynamic response of the numerical substructure for hybrid simulation, in particular for complex structural systems. The computing efficiency of finite element analysis can be improved through multi-threading with parallel finite element algorithms. Thus, a GPU-based computing system can shorten the elapsed time and reduce the experimental error of a hybrid simulation. For data acquisition system, the SSL possesses a 32-channel MTS FlexDAC™ 20 for acquiring experimental data of strain and bridge-type devices. Meanwhile, the NI PXI system mentioned previously has 88 analog inputs which can be also used for collecting experimental data with a high sampling rate of up to 15.6 kHz particularly for structural specimens with impact dampers (Lu *et al.* 2017). For material testing, the SSL is equipped with an MTS 810 material testing system that can be used to conduct high cycle fatigue testing for nonstructural components. The maximum stroke and force capacity of the system are

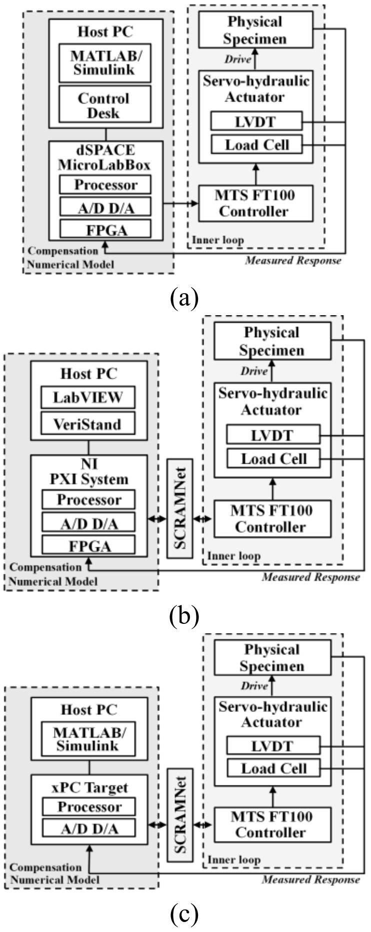


Fig. 10 Potential application framework for single RTHS (a) dSPACE™ MicroLabBox application (b) NI PXI System application (c) xPC Target™ application

±75 mm and ±100 kN, respectively. Last but not least, a portable uni-axial shake table is assembled in the SSL for academic and educational purposes. An ancient servo-hydraulic actuator with a force capacity of ±15 kN is used to drive the table via two linear guides with slight friction. The platen of the shake table is made of aluminum and small-scale specimens can be mounted on the platen through M6 bolts. The payload and the bandwidth of the shake table are 3 kN, and 0.1 Hz to 50 Hz, respectively. The shake table can be also used for validating novel shake table control algorithms considering control-structure interaction with limited and affordable expenses. Furthermore, the shake table can be used with additional actuators which forms a hybrid application for validating novel and advanced experimental methods.

3.2 Potential application framework

Potential future application of the hardware and software for developing and validating novel experimental methods in the SSL is introduced conceptually in this section. For real-time hybrid simulation with elastic structural responses, Fig. 10 illustrates the prospective experimental layout for single application for simple RTHS. The compensation algorithm and numerical substructure of

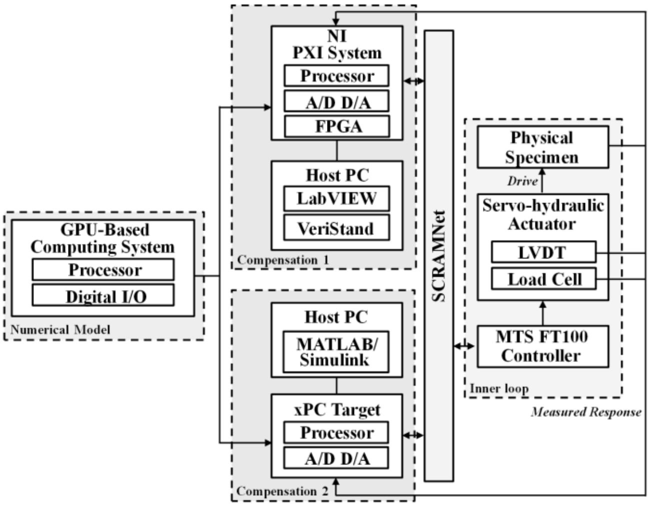


Fig. 11 Potential advanced application framework

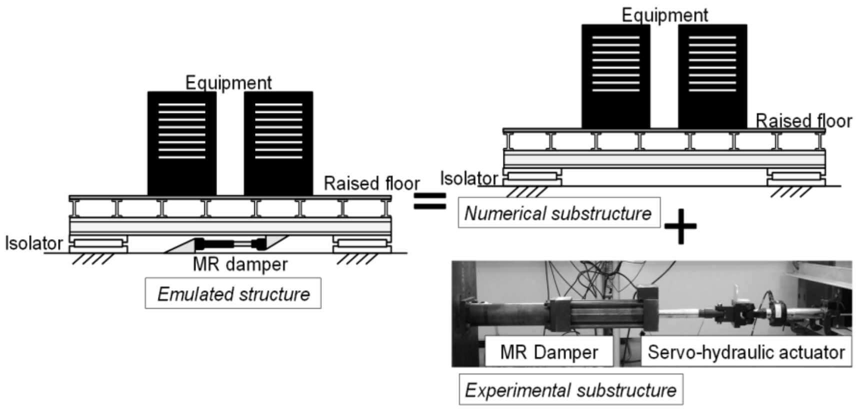


Fig. 12 Schematic of the numerical and experimental substructures of the RTHS demonstration

a RTHS can be running in any one of the real-time computing platforms such as dSPACE™ MicroLabBox (Fig. 10a), NI PXI system (Fig. 10b), and xPC Target™ (Fig. 10c). Each real-time computing platform is connected to a host PC through TCP/IP. Each host PC is running respective software; for example, the host PC of the NI PXI system is running LabVIEW™ and VeriStand™ (Fig. 10b). It is noted that the dSPACE™ MicroLabBox is the only platform that cannot exchange the data with the MTS FlexTest® Controller FT-100 digital controller through SCRAMNet. However, analog I/O is still an alternative for data transferring as long as the measurement and background noise can be reduced appropriately. For advanced and complex application such as DRTHS and multi-degree-of-freedom (MDOF) RTHS, Fig. 11 depicts the potential experimental layout. The NI PXI system and Mathworks® xPC Target™ can be used simultaneously by forming a ring topology of SCRAMNet and transferring the data between the computing platforms and digital controller with 2.5 Gbit per second. Meanwhile, the GPU-based computing system can be adopted to accelerate the numerical integration through parallel computing. The computed responses can be sent to the real-time computing platforms through digital I/O.

4. Experimental demonstration

The first real-time hybrid simulation completed in the SSL was a smart base-isolated raised floor system, which was composed of nine sloped rolling-type isolation devices, four magnetorheological (MR) dampers, and one raised floor system. The isolation devices are distributed evenly underneath the raised floor with 300-mm isolation clearance in the horizontal direction. For RTHS, the isolation devices, the raised floor, and the protected equipment were simulated numerically while one of the MR dampers was tested in the laboratory for simplicity purpose as depicted in Fig. 12. The MR damper was pin-connected to one of the servo-hydraulic actuators at one end and connected to a reaction support at the other end. The hardware and software framework for the experimental demonstration is depicted in Fig. 13 which was slightly modified from the typical framework shown in Fig 10a. The dSPACE™ MicroLabBox was adopted for solving the equation of motion of the numerical substructure. The computed displacement command was then compensated by the phase-lead compensator to reduce to effects of time lag and delay (Chen and Tsai 2013). Furthermore, the control command for the MR damper was also calculated and sent

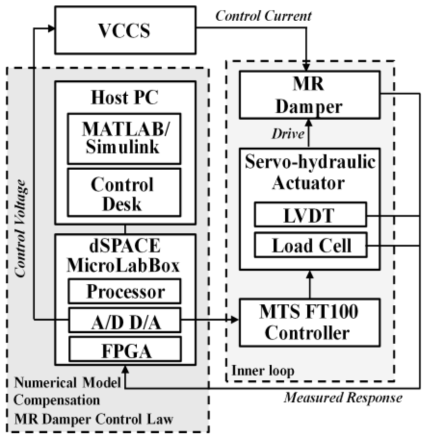


Fig. 13 The hardware and software framework of the RTHS demonstration

to the MR damper in real time. However, the control command computed from the MicroLabBox was a voltage signal with negligible small current. Thus, a voltage control current source (VCCS), manufactured by Lord Cooperation, Cary, North California, was adopted to convert the computed control voltage to a control current. Experimental results demonstrate that RTHS can be completed successfully by using the application framework in the SSL. In addition, it is proved that RTHS provides a cost-effective method to investigate the seismic performance of the smart base-isolated raised floor system. More details of the RTHS of smart base-isolated raised floor system can be found in reference (Chen *et al*. 2019).

5. Potential future application

The SSL is equipped with state-of-the-art servo-hydraulic and control system as well as modern hardware and software framework, future potential applications for developing and verifying the novel experimental methods for earthquake engineering studies are introduced in this section.

5.1 Testing method using shake table and actuator

A seismic shake table is used to reproduce historical or artificial earthquake acceleration time histories; therefore, the corresponding response of the specimen mounted on the shake table can be investigated. Shake table testing has been incorporated into RTHS method, leading to an innovative application for earthquake engineering. This method is named hybrid shake table and has been applied to investigate the seismic response of shear buildings (Zhang *et al.* 2016), midlevel seismic isolated buildings (Schellenberg *et al.* 2017), and buildings with tuned liquid dampers (Wang *et al*. 2016). These studies separated a MDOF shear building into an upper and a lower substructure. The lower substructure was numerically simulated and the response (either displacement or acceleration) at the interface between the upper and lower substructures was reproduced by the shake table in real time.

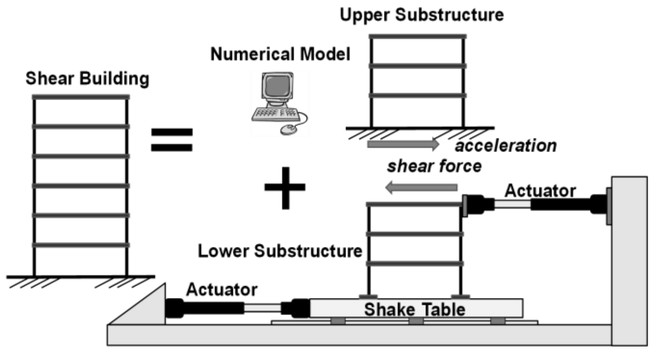


Fig. 14 Schematic of the potential novel testing method with a shake table and an actuator

Unlike conventional shake table testing, the response trajectory was not recognized prior to testing. Therefore, controller for the hybrid shake table testing must be analyzed and synthesized appropriately to achieve accurate control and stability in RTHS.

The upper substructure, on the other hand, can be simulated numerically instead of the lower substructure. The lower substructure is mounted on the shake table; therefore, it is subjected to real ground motion reproduced by the shake table. The corresponding absolute acceleration at the interface between the upper and lower substructures is obtained and then used as the input acceleration to the numerically-simulated upper substructure. The corresponding shear force at the interface is imposed on the experimental substructure through force control of an actuator. Fig. 14 illustrates the concept of a RTHS with a shake table and an actuator. The force-controlled actuator is attached to the top floor of the lower substructure. Both the shake table and actuator are driven in real time which is similar to the test that was completed by MTS Systems Corporation and Tongji University (Yang *et al*. 2015). In their study, the whole bridge specimen was fixed on a shake table and one actuator was attached to the specimen at the center of girder. The inertial force of the bridge deck was applied by the actuator. Although the RTHS combined a shake table and an actuator, the force applied on the physical specimen was limited to inertial force. For the potential application, the applying force considers not only inertial force but the base shear from the dynamic deformation of the upper substructure. The challenges and difficulties of this ongoing development of testing method are the noise rejection of the transmitted floor acceleration from the top of the lower substructure to the bottom of the upper substructure; the synchronization between the transmitted shear force and the ground acceleration; and the force tracking control of the actuator acting on a flexible lower substructure. Consequently, researches related to force-based RTHS remain rare which could be one of the most challenging tasks for RTHS. The SSL provides the users with a simple environment to develop this demanding experimental method in a safe and cost-effective manner.

5.2 Multi-degree-of-freedom active mass damper

Active mass damper (AMD) control system has been

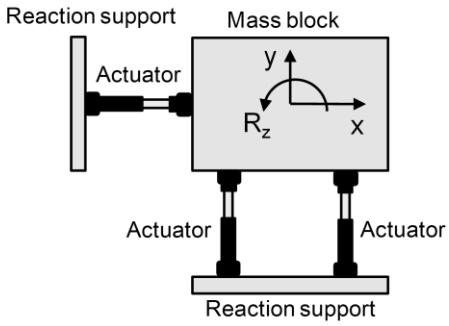


Fig. 15 Illustration of the top view of an active mass damper system for suppressing in-plane vibration

extensively adopted and applied for vibration control of high-rise buildings subjected to wind loading such as the Yokohama landmark tower in Yokohama and Abeno Harukas in Osaka in Japan. The AMD employs actuators, sensors, and feedback control algorithms to apply control force and suppress vibrations due to wind loading. Various control algorithms have been proposed and verified for the past decades such as linear quadratic regulator, time delay control algorithm (Jang *et al.* 2014), and adaptive fuzzy control (Soleymani and Khodadadi 2014). However, most of the studies were focused on the control algorithms for a single-degree-of-freedom AMD. In other words, the AMD was used to reduce the vibration in one principle direction without considering the other orthogonal and rotational directions.

A general AMD control system used to suppress in-plane responses of structures needs to apply control force in two orthogonal and one rotational directions. However, the AMD control accuracy is significantly affected by the cross-axis sensitivity especially, the rotational degree of freedom is considered. Accordingly, incorrect control performance of the AMD could be achieved. It is practical and cost-effective to verify the control accuracy of a MDOF AMD prior to large-scale structural testing in the SSL as it is equipped with six 15-kN servo-hydraulic actuators. A typical 3DOF AMD system is illustrated in Fig. 15. It is assumed that the mass block is a rigid body and the reference point is the center of gravity of the mass block. Developers can implement novel and modern control algorithms to verify the control performance of the AMD.

6. Conclusions

Advanced and novel experimental techniques for evaluating dynamic responses of structures subjected to ground motions in an economical and effective manner have become indispensable for earthquake engineering researches. However, the risk of damaging specimens or facilities during the development and validation stage of new experimental methods are unavoidable. Regular testing could be postponed if the facilities in a structural laboratory are damaged which would lead to significant consequences of delay of various research projects. Most of the earthquake engineering laboratories have been facing the dilemma of running regular research experiments or developing essential novel experimental techniques since the equipment and facilities are exclusive. In order to solve the dilemma and provide the developers and researchers with a cost-effective and safe environment for validating newly developed experimental technique, a small-scale structural laboratory (SSL) has been designed and constructed in NCREE. In this paper, the design and analysis details of the SSL as well as the essential hardware and software are introduced including the hydraulic and control systems, real-time computing platforms, steel specimen with replaceable nonlinear components, and other equipment. A simple application of real-time hybrid simulation for a smart base-isolated raised floor system that utilized the facilities in the SSL is demonstrated, approving the hardware and software framework is helpful to validating new experimental methods before they can be applied to testing in large-scale structural laboratories. Finally, two potential studies are addressed and discussed which used to be exceptionally perilous but become applicable in the SSL. It appears that this SSL provides a general framework to verify innovative concepts for earthquake engineering studies with acceptable and reasonable risks for developers.

Acknowledgments

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